# FireGrid: Integrated emergency response and fire safety engineering for the future built environment

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## Abstract

Analyses of disasters such as the Piper Alpha explosion (Sylvester-Evans and Drysdale, 1998), the World Trade Centre collapse (Torero et al, 2002 , Usmani et al, 2003) and the fires at Kings Cross (Drysdale et al, 1992) and the Mont Blanc tunnel (Rapport Commun, 1999) have revealed many mistaken decisions, such as that which sent 300 fire-fighters to their deaths in the World Trade Centre. Many of these mistakes have been attributed to a lack of information about the conditions within the fire and the imminent consequences of the event.

E-Science offers an opportunity to significantly improve the intervention in fire emergencies. The FireGrid Consortium is working on a mixture of research projects to make this vision a reality. This paper describes the research challenges and our plans for solving them.

## Introduction

Computational Fluid Dynamics (CFD) fire models and Finite Element (FE) structural models have advanced to the point where they can provide approximate engineering estimates to the spread of fire and its effects on structures. Planning-based command and control ($C^2$) systems are already used in evacuation planning. Together they will allow the generation of evacuation scenarios in anticipation of future fires. These are sufficient to guide better building design. We call this the "Design mode" of FireGrid.

The same technologies will also support training of emergency response teams . The $C^2$ system will be extended with simulated agents and simulated external events, based on the scenarios generated in design mode. This is the "Training mode" of FireGrid.

In FireGrid's "Emergency Response" mode, parallelisation and on-demand Grids will allow the same CFD and FE models to be run faster than real time. Pre-deployed sensors and wireless networks will obtain data from the burning building which will be used to guide and accelerate the computations. Data from the computations and sensors will be input to the real-time planner. The same wireless networks will enable the $C^2$ system to direct the first line of defences – alarms, sprinklers, fans, vents and similar devices. Finally, human responders – fire-fighters – will have much more information to guide their response.

Conventionally research based on experiments and computational modelling have been considered to be separate activities. FireGrid offers an opportunity to draw the two methodologies together in order to gain special insights into problems that would not be possible using one or the other in isolation. Computational forecasting of developing events in real-time would potentially enable exploitation of experiments and computation interactively as a single integrated research tool (with no requirement of geographical contiguity). Experiments could focus simulations on points of interest, and vice versa, in a manner analogous to user-guided computational steering (Brooke et al, 2003). The development of techniques and protocols to enable real-time interaction between experiments and (high performance) computation should only involve minor modifications to the primary modes of FireGrid but should produce a very powerful and novel research methodology, allowing FireGrid to be used in "Research mode".

## The FireGrid Consortium

The FireGrid consortium brings together many bodies with an interest in improving response to fire emergencies. It is led by the School of Engineering and Electronics at the University of Edinburgh and is currently supported by an EPSRC network grant. Members include:

- Emergency Planning and Response organisations (Fire Brigades and the

Fire Research Division of the Office of the Deputy Prime Minister)

- Engineering & Technology Consultancy Companies (Arup and Building Research Establishment (BRE))
- Computational Software and Sensing Technology Companies (Vision Systems, ABAQUS, ANSYS)
- National Research Laboratories (NeSC, NIST, IRSN, TNO, HSL)
- Universities and Colleges (Edinburgh, Imperial, Queen Mary, The Fire Service College, IHPC Singapore)

Members of the consortium are collaborating in requirements analysis, in the planning of system evaluations, and in research proposals. The first FireGrid requirements workshop was held on 18th April 2005; presentations are online at the consortium web site (http://www.firegrid.org).

## FireGrid technologies

From the technology point of view, FireGrid is primarily about integrating several technologies, extending them where necessary:

- High Performance Computing (HPC) (of CFD fire models and FE structural models)
- Wireless sensors (in extreme conditions with adaptive routing algorithms, including input validation and filtering)
- Grid computing (including sensor-guided computations, mining of data streams for key events and reactive priority-based scheduling and )
- Command and Control ($C^2$) (using knowledge-based planning techniques with user guidance)

Figure 1 shows how the contributing technologies will be integrated. We plan a series of pairwise experiments that gradually develop the full system, with detailed evaluations at each stage. Every stage will generate new research challenges, results & papers. Some of these experiments are already underway, funded as individual research projects

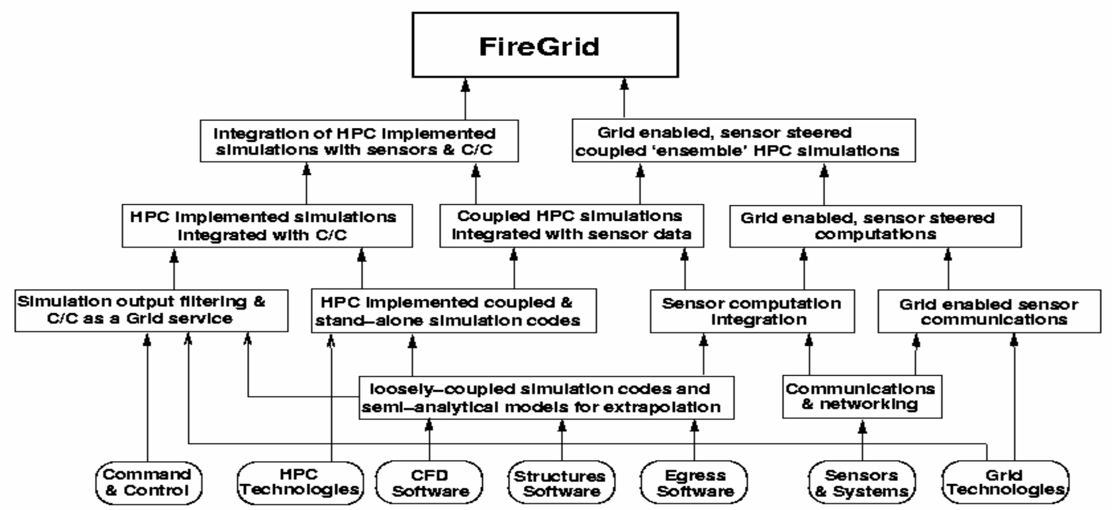


Figure 1: Integration of FireGrid technologies

## HPC

FireGrid integrates several existing modelling packages. These will be enabled as Grid components. Where necessary, OpenMP will be used to parallelise sequential codes. All these components will be loosely coupled to model all aspects of a fire scenario.

For the emergency response mode, these components will have to simulate the fire in super-real-time. This poses a significant computational challenge. A typical hotel room simulation of a 15 minute event requires 6 hours of CPU time on a PC with 1 GB memory. Scaling this up to model a large hotel would thus produce a problem which would require state-of-the-art HPC resources to model in super-real-time. To achieve this goal of super-real-time capability a combination of algorithmic simplification and parallel computing is required.

The emergency response mode of FireGrid does not rely upon high accuracy in the CFD predictions of the entire event, which would be an unrealistic expectation. Instead, we can combine extrapolation with continuous verification from the sensor data. This makes viable the use of simplified physical models in combination with CFD codes. Complete CFD codes are executed for short time intervals, and continuous feeds of data are used to calibrate models that simplify the most computationally intensive areas of the calculation in real-time. This allows rapid extrapolation of the progress of the event for time scales much larger than the fully computed periods.

A key research topic is to make efficient use of sensor data to steer and accelerate simulations in this way. In addition, we can run simulations in parallel, discarding those that do not match the sensor input and replacing them with new simulations.

## Sensors

A typical FireGrid scenario could involve 10,000 sensors. The role of these sensors is to monitor the environment and ensure that information on the environment is delivered where it is required. In FireGrid it is envisaged that the sensor network will also perform initial data validation and filtering to minimise data transfer and also minimise false alarms.

The number ofsensors envisaged precludes the use of many conventional algorithms and demands a hierarchical architecture that deals with the different types of sensors (e.g. smoke, CO, temperature, etc), the different types and ranges of information, and the variable data rates from individual sensors. The data rates will be modest, typically updates on a 0.1-1s interval with a few kilobits per sensor.

This hierarchical structure will work on several levels, i.e. on a routing level, on a location basis, and by sensor type, thus enabling the management of the large number of sensors and the data they will provide.

The reliability and durability of the sensors in a fire are essential to the success of this work and will require investigation. The survivability of a sensor implies some form of shielding from the environment which will have implications for the sensitivity of the sensors and for the communications technology. The likelihood of sensors being destroyed suggests that the communications network will have to self-organize without prior knowledge of the network topology. It is not sensible to consider the conventional star topology with strong centralised control for such a sensor network, as there would be a major risk of the system collapsing with the failure of single elements.

Topics to be investigated using a range of existing linked cluster ad-hoc routing algorithms for wireless-based sensor networks will be the need to adapt to propagation conditions, node destruction and failure. Of particular interest here is how to route the data in a robust manner and also deal with a sensor network that could be of the order of thousands of sensors. To date much of the research in ad-hoc networks has focussed on networks with a maximum of 1000 individual elements but generally considerably fewer.

A research challenge is to identify key events from the large amount of sensor data. We plan to run data mining and other codes on processors close to the sensors to detect subtle changes in the environment. The system will also analyse the multiple sensor inputs and compare them to typical fire "signatures," thus authenticating the data and avoiding false alarms.

## Grid

Grid-enabled distributed computing is vital to the success of this project. The Grid will support the co-ordination of all remote resources and people. Each subsystem of FireGrid is envisaged as a Web Service with a well-defined set of interfaces and behaviours, able to communicate in standard ways with the other subsystems using a mixture of communications protocols as required.

Design mode requires the integration of the fire modelling code, plans of the building, and the $C^2$ system. Modelling of the different aspects of a fire involves the input, management and output of very large quantities of information. We plan to implement remote HPC job submission and control through the Globus Toolkit (Foster, 2005). We will implement remote access to distributed, heterogeneous databases of model input data using OGSA-DAI (Antonioletti et al, 2005).

The $C^2$ system expects input in the form of discrete events and information of interest. It will generate options which might be explored for emergency response plans and will use this information to guide which simulations to run. An interpretation layer will analyse the results of each simulation to extract the information of interest.

Design mode will allow for the creation and storage of emergency response plans or components of them. These need to be indexed in a form usable by the $C^2$ system, for example to select partial responses to its input events. This will enable the system to find and load relevant response options for unfolding events.

The emergency response scenario presents unusual demands on HPC systems: it requires rapid access to significant resources at unpredictable times. It is unlikely that a single resource could be devoted to this application, as it would result in an expensive piece of hardware lying largely idle until required in an emergency situation. A more realistic approach is to be able to access such resources on-demand, recruiting existing HPC facilities at short notice. This will require these systems to support priority scheduling, displacing any mundane work currently executing. Most current HPC scheduling systems do not support this form of scheduling; rather, they optimise the maximum throughput of the resource (Andrieux et al, 2004). Therefore FireGrid requires new workload schedulers and policies.

It may be advantageous to be able to potentially access a large number of resources, both as a form of redundancy against failure, and as a means to exploit multiple resources to execute successive forecast runs. This requires dynamic discovery of resources, using a Grid registry system such as MDS (Zhang, et al, 2003). An important function of the Grid will be to allow escalation of the computer resources involved as the event increases in magnitude.

The other key demand made by the emergency response mode is that the sensor input must be routed to the simulations. The sensor net as a whole will be wrapped in a Grid service to allow it to interface with the rest of the system, building on as yet unpublished work from the EQUATOR-MIAS project. Thus the intricacies of the sensor routing algorithms will be hidden from the rest of the system, but the system will be able to access the data stream from the sensors.

As with the results of simulations, an interpretation layer will filter the sensor data for key events. This data mining capability will be incorporated in the Grid service wrapper of the sensor net itself. These data filters must be updated as the event progresses, in order to look for the most relevant events.

The research mode of FireGrid will maintain the close links between sensors and computation. In addition it will leverage visualisation and steering components to allow researchers to direct the computation towards areas of interest, as in the successful RealityGrid project (Brooke et al, 2003).

Thus the architecture demanded by the FireGrid system is thus fundamentally distributed, heterogeneous and loosely coupled. It requires significant computational power to be made available on-demand, with little advance notice; it needs to couple multiple high-performance simulations with remote databases of maps and building structures; it needs to assimilate data from thousands of sources in a sensor-rich environment; and it needs to interactively communicate with building management and control systems and human beings – firefighters, for example – in hazardous, wireless environments. All of these will be co-ordinated by the grid-enabled $C^2$ system, which will also allow the participation of remote experts to give advice.

The performance and reliability of the Grid middleware layers, is of paramount importance. We expect FireGrid to severely stress current implementations. Performance bottlenecks will be identified and resolved.

There will be longer term issues related to Grid development which will need to be addressed in future to enable FireGrid to be deployed beyond the research stage.

Watertight mechanisms for authentication and authorisation are essential to FireGrid. A strong web of trust between the different components of the virtual environment is crucial to such a life-critical system. Highly secure proxy authentication mechanisms are required to propagate the authority of the command system to enable the "requisitioning" of significant – and expensive – computational and data resource at very short notice.

A fully-deployed emergency response Grid will pose particularly onerous security requirements.

As an extreme example, consider an arson attack on a building protected by FireGrid. If the attackers are aware of the FireGrid installation, they could launch a co-ordinated cyber-attack to prevent the FireGrid system responding to the arson attempt. There is a possibility that an installation will come to rely on FireGrid, thus weakening conventional response mechanisms, making the security issue vital in this context.

The performance of all aspects of the system is critical – delays in the FireGrid system could cost lives. Quality of service is a fundamental aspect of Grid computing that has only begun to be investigated. The demands that FireGrid will make of network and resource performance will offer major insights into QoS mechanisms for future Grids. It may be possible for FireGrid to be a testbed for QoS across the SuperJANET framework, through exploring links with QoS projects (Olifer and Samani, 2005).

# Command and Control

The Command and Control ($C^2$) task can be defined as the exercise of authority and direction over available resources towards the accomplishment of some objective. The standard application of $C^2$ is found in military contexts, but the same concepts apply to civilian situations where there is a clear need to impose control and marshal resources. Firefighting is one such situation.

The $C^2$ process consists of repeated cycles of a number of subtasks, namely: the collection of data from sensors and other sources; the analysis of these data and the current situation in general; the choice of a particular course of action to take; planning for the enactment of this action given the available resources; the direction of the resources to enact the plan; and finally, the assessment of the outcomes of the enacted plan. It should be emphasized that the goal of $C^2$ systems is *not* to automate this entire process. In FireGrid, the first responses may well be automated – sprinkler systems, halon gas, evacuation signs, etc., but when humans join the loop the role of the $C^2$ system is to facilitate this cycle and support the human decision-maker. The $C^2$ system is the 'glue' that holds a response organisation together.

In the FireGrid design mode, the $C^2$ system will assimilate data from building maps and fire models and evaluate the suitability of automated responses. It will support "what-if" exploration of possible scenarios, guided by the design team. This will provide valuable feedback on the building design.

Design mode will generate and store a multiplicity of potential emergency response scenarios. In training mode the $C^2$ system will use these, in conjunction with simulated agents, to support simulations and prepare potential responders for the likely emergency events.

In emergency response mode, the $C^2$ system will be a bridge between Grid services and emergency responders by assimilating incoming data of the current fire, by allowing the retrieval and presentation of appropriate maps and fire models from databases, by facilitating the initiation of simulation jobs and presenting the results in an appropriate form, by assisting in the construction and elaboration of suitable response plans, and by allowing the communication of actions to emergency responders on the ground.

In common with a number of $C^2$ systems in the past, this system will draw upon Artificial Intelligence concepts, specifically knowledge-based and planning techniques. Much modern AI research is focused on providing support to human agents (and as such corresponds well with the objectives of $C^2$ system builders). The impetus for this lies in an acknowledgement of the differing capabilities of humans and computers, and its aim is to engineer environments where these capabilities will complement each other to greatest effect.

The I-X programme (Tate, 2000) is typical of this type of modern AI project. Its overall aim is to create an enabling environment for mixed-initiative (i.e., involving both human and computer agents) activities. I–X draws on (and is a natural successor to) several decades of AI experience in planning, scheduling and, more recently, process, workflow and activity management. Born of this experience, and lying at the conceptual heart of the programme, is a unifying upper ontology for a shared representation of a task, whatever the precise nature of the task or its domain may be. This conceptualisation, the *<I-N-C-A>* ontology (Tate, 2002), is based on the notion of both the processes governing the task and the artefacts emerging from it being composed of abstract 'nodes', whose relationships are described by a set of constraints. Issues relating to the current nodes are cyclically generated and resolved so as to refine the set of nodes and their relationships and, in so doing, move the task forward. This model allows flexibility in the extent and nature of the formalisation of the representation. As well as encouraging a principled encapsulation of the task, the model also provides the basis for a systems architecture and communication framework, allowing the concrete realisation of I–X systems.

For a human user, the principal interface to the I-X technologies is a *Process Panel* (Tate, Dalton and Stader, 2002). Process Panels present to users the current state of the collaboration from their individual perspectives, and allow them to decompose activities, refine elements of the plan, delegate issues, and invoke automated agents, all serving to move the overall task toward completion. Libraries of 'standard operating procedures' can be accessed to provide model plans for archetypal activities (such as 'best practice' responses to particular types of fire). In addition to this activity management engine, a panel gives its user access to domain-editing and planning tools, visualisations of the collaboration space and agent-relationship editors (figure 2 shows some of the I-X tools).

In addition, to fully realise the $C^2$ aspect of FireGrid, it will be necessary to engineer knowledge-based support layers to, for instance, abstract the raw sensor data into meaningful concepts (e.g., "the central stairwell is on fire") and interpret simulation results ("the ceiling of the central stairwell will collapse in 10-15 minutes") so as to provide 'intelligence' for decision-making. Another key aspect will be the provision of suitable visualizations of this information, allowing for the most immediate communication of its content.

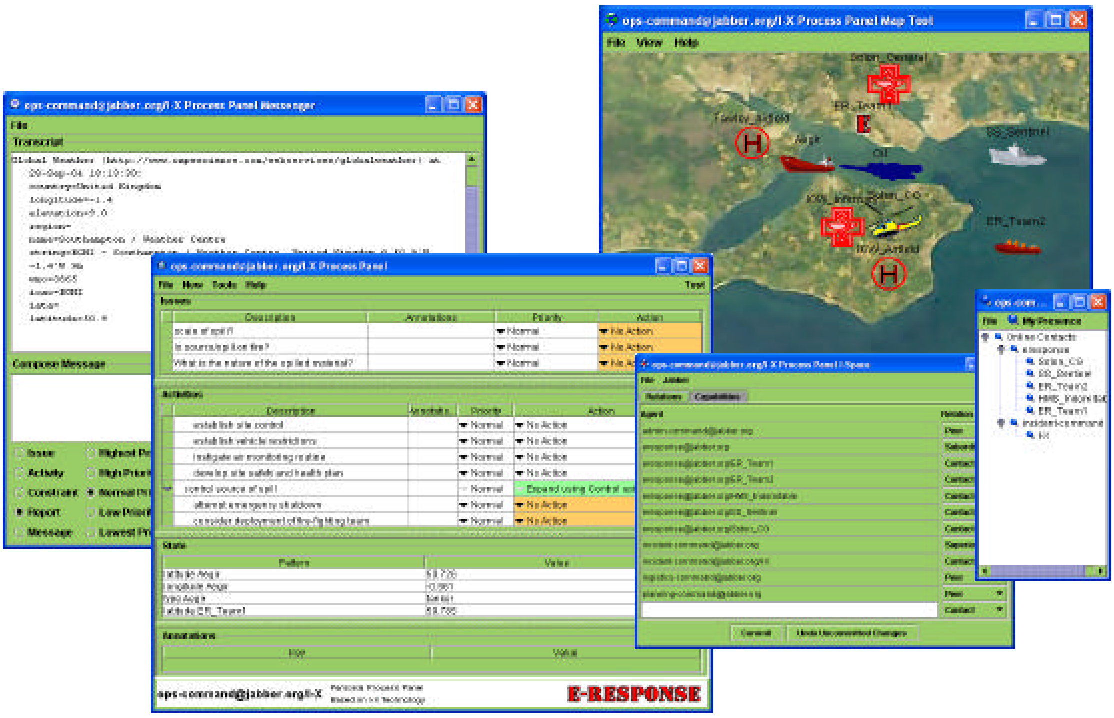


Figure 2. An I-X Process Panel, and its accompanying tools, shown here engaged in coordinating the response to a simulated environmental emergency.

## Evaluation

Clearly a system such as FireGrid demands careful evaluation. We have planned a series of tests, beginning with the initial pairwise technology experiments outlined in Figure 1. These integrations are projects in their own right and will involve careful testing.

For the full-scale integration, we will use the facilities at BRE to undertake a well-instrumented full-scale fire test in a realistic multi-storey building. This will test the whole system under realistic conditions. The fire scenarios are of equivalent scale to real events and thus permit full use of the physical models. This requires our own installation of sensor equipment and destruction of most of the instrumentation.

In this test burn, we will compare the sensor information against the predictions of the software, and evaluate the reliability of the sensor network and the performance of the $C^2$ system. Crucially, we will hold a de-brief meeting with fire staff and learn from their reactions.

## Current Status

The FireGrid Consortium is in place and has held its first requirements workshop. We have recently been awarded funds from the DTI for the substantial R&D effort needed to meet the challenge of integrating the various technologies into a prototype system. In addition, we plan to address the research questions in FireGrid via a range of projects. Currently submitted research proposals address topics such as "Sensors in Extreme Environments" and "Coupled Testing and Computation: in study of laterally restrained heated RC Slabs".

## Related Work

Our plans for FireGrid build on established bodies of work in each of the component technologies, which we do not review in this paper. The novelty and challenges lie in the integration of these technologies, where considerably less work exists.

A project of particular note is the EU-funded RUNES project (http://www.ist-runes.org) which considers embedded sensors in a range of applications. These applications include emergency response but their scenario and approach is different to that of FireGrid. The RUNES scenario is about guiding emergency responders through the area surrounding an emergency, providing information about the location of response teams and threats via GPS and other sensors. It does not deal with the close coupling of the sensor data with computation nor deal with issues of data validation and filtering which will be vital in FireGrid. Furthermore, the RUNES project does not have the concept of modes in which scenarios are generated in advance and used for design, training and to guide responses in the event of an emergency.

The FireGrid scenario is more advanced than RUNES in that we add the modelling elements. Conversely RUNES is more adventurous in their use of sensors because they have a requirement to deal with multiple types of sensor network and to download code to reconfigure the sensor networks. They are developing a configurable general middleware for sensor devices (Costa et al, 2005); our goals for our work with sensors are focussed on our particular needs. They have (like many projects) done useful work on reconfigurable wireless networks (Baldoni et al, 2005).

Several teams are researching the use of sensors in Ubiquitous Computing (see, e.g., http://www-dse.doc.ic.ac.uk/Projects/UbiNet/). As with the RUNES project, this work does not deal with the modelling and simulation aspects that are central to the FireGrid vision

Sensornet (http://www.sensornet.gov/) is an ambitious project to integrate disparate sensors in the environment to detect a range of chemical, biological or nuclear threats. The system envisages a range of applications that could use this data, one of which would produce a real time model of the spread of the threat though the atmosphere. The results of this computation would then be made available to emergency response teams. The focus of this system is on geographical modelling. It is not Grid based.

CFD codes and multi-variable analysis similar to those planned for FireGrid have been used for pollution control in industrial combustion systems (Carvalho, 1999). The complexity of the fire scenario implies a significant extension to the methodologies reviewed by Carvalho. The coupling of CFD codes to these simplified computational architectures is an important aspect of this project.

## Summary

FireGrid is researching the development and integration of modelling, sensors, Grid, HPC, and $C^2$ technologies. It will stimulate further research, in new safety systems and strategies, in new sensor technologies, in improved modelling techniques and in Grid technologies and operation.

By integrating previously uncoupled tools, FireGrid will allow true performance-based design for the built environment. It will introduce a new emergency response paradigm, using scenarios planned and stored in advance in conjunction with super-real-time simulation. Deployment of FireGrid will reduce costs and save lives.

## Acknowledgements

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